Drivers of declining CO_2 emissions in industrial countries

Authors and affiliations:

Le Quéré, Corinne, Tyndall Centre for Climate Change Research, University of East Anglia, UK

Korsbakken, Jan Ivar, Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway

Charlie Wilson, Tyndall Centre for Climate Change Research and School of Environmental Sciences, University of East Anglia, UK

Jale Tosun, Heidelberg University, Institute of Political Science and Heidelberg Center for the Environment, Heidelberg, Germany

Andrew, Robbie, Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway

Andres, Robert J., Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Canadell, Josep G., Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, Australia

Jordan, Andrew, Tyndall Centre for Climate Change Research and School of Environmental Sciences, University of East Anglia, UK

Peters, Glen P., Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway

van Vuuren, Detlef, PBL Netherlands Environmental Assessment Agency, 2594 AV, The Hague, The Netherlands, and Utrecht University, Copernicus Institute for Sustainable Development, Heidelberglaan 2, Utrecht, The Netherlands

Global emissions of carbon dioxide (CO_2) from fossil fuels and industry increased by 2.2% per year on average between 2005 and 2015[1]. Global emissions need to peak and decline rapidly to limit climate change to well below two degrees Celsius of warming[2,3], one of the goals of the Paris Agreement[4]. Untangling the reasons underlying recent changes in emissions trajectories is critical to guide efforts to attain those goals. Here we analyse the drivers of decreasing CO_2 emissions in a group of 18 industrial countries that have decarbonized over the period 2005-2015. We show that within this group, the displacement of fossil fuels by renewable energy and decreases in energy use explain decreasing CO_2 emissions. However the decrease in energy use can be explained at least in part by a lower growth in GDP. Correlation analysis suggests that policies on renewable energy are supporting emissions reductions and displacing fossil fuels in these 18 countries, but not elsewhere, and that policies on energy efficiency are supporting lower energy use in these 18 countries as well as more widely. Overall, the evidence shows that efforts to reduce emissions are underway in many countries, but they need to be maintained and enhanced by more stringent policy actions to support a global peak in emissions followed by global emissions reductions in line with the goals of the Paris Agreement[3].

Fossil fuel CO_2 emissions are the main cause of human-induced climate change[5]. Historically, they have increased over timescales of many decades in all countries[6]. However, since the mid-1970s, emissions have peaked and subsequently declined consistently in several European countries, initially because of energy resource substitutions from coal to oil, gas and nuclear power. Since the early 1990s, transfers of emissions through international trade have also contributed to emission reductions in some countries[7,8], although this effect stabilized around 2005 in most developed economies[1]. In the period since 2000, global fossil fuel emissions have increased rapidly driven by the rapid industrialization of China[1,9]. Yet, emissions in the USA and in Europe have decreased for over a decade, reducing the rate of increase globally[9].

Understanding the drivers of emissions trends in countries where emissions are consistently decreasing could indicate whether efforts to decarbonise energy systems and tackle climate change are truly in motion, or whether they are simply reflecting secular trends in national and global economies. In addition, despite significant attention given to policies and measures to tackle climate change[4,10], it is not clear if they have significantly influenced national emission trends consistently across all countries[10-13]. The scale of government and non-government led actions to reduce emissions has grown in recent years, but a broad assessment of their overall effect is largely missing.

In this analysis, we use national CO_2 emissions from fossil fuel combustion from the International Energy Agency (see Methods). We isolate a 'peak-and-decline' group of 18 countries where emissions have significantly decreased over the period 2005-2015 considering both territorial and consumption emissions (Fig. 1; Supplementary Figure S1). The peak-and-decline group represents 28% of global emissions. We also select two control groups for reference. Both control groups include countries where emissions have not significantly decreased, but distinguish low GDP growth (group A, 30 countries) and high GDP growth (group B, 31 countries; see Methods).

Emissions in the peak-and-decline group decreased by –2.4% [–2.9% to –1.4%] per year on average during 2005-2015 (Table S1-S2; numbers indicate the median and 25-75 percentile; see Methods). To understand why, we decompose country-level emissions trends among four contributing factors representing physical drivers (Table 1; see Methods): (1) energy use – changes in final energy, attributable to changes in the efficiency with which energy services are provided and consumed; (2) fossil share – changes in the share of fossil fuels in final energy (including electricity and heat generated from fossil fuels), reflecting the displacement of fossil fuels by non-fossil energy including renewables and nuclear; (3) fossil utilisation rate – changes in the ratio of fossil final energy over fossil primary energy, representing energy consumed or lost in energy extraction, conversion and transmission; and (4), fossil CO_2 intensity – changes in the carbon intensity of fossil energy, reflecting the proportion and fuel quality of coal, oil and gas in the overall fossil fuel mix.

Results show that the largest contribution to emissions decreases in the peak-and-decline group for 2005-2015 was from decreases in the fossil share of final energy, accounting for a median of 47% [36 to 73%] of the decrease in emissions (Fig. 2), and decreases in energy use, accounting for 36% [18% to 56%]. There was no substantial contribution at the group level from changes in fossil utilisation rate or from changes in fossil CO_2 intensity (Fig. 2). Outsourcing of emissions through trade was small relative to these four physical drivers and does not account for their substantial contribution to CO_2 reductions (Fig. 2). Results were similar across available datasets (Table S3).

Some country-level variation within the peak-and-decline group is notable (Table S3-S4). First, contributions to emissions decreases in the USA were more evenly distributed across the four drivers, with the largest single contributor coming from the switch from coal to gas driven by the availability of shale gas. Second, the contribution of decreases in the fossil share of energy alone dominated emissions decreases in Austria, Finland, and Sweden, consistent with a rising market share of renewables in power generation and/or heat. Finally, the contribution of reductions in energy use dominated emissions decreases in France, Ireland, Netherland, Spain, the United Kingdom, as well as the EU28, despite the economies growing.

These drivers of emissions in the peak-and-decline group were distinct from those of the control groups, where changes in emissions are dominated by changes in energy use alone. In group A (low GDP growth), increases in energy use accounted for 75% [–11 to 130%] of the increase in CO_2 emissions, with no substantial contributions from the three other factors (Table S5; Fig. S2). In group B (high GDP growth), increases in energy use accounted for 79% [58 to 90%] of the increase in CO_2 emissions, with an additional contribution of 16% [2 to 29%] from the rising share of fossil energy in final energy. Many rapidly growing economies are seeing coal and oil's share rising faster than renewable or other low-carbon energy.

Changes in CO_2 emissions in the peak-and-decline group differ from previous changes observed since 1960 (Fig. 3). During the 1960s and 1970s, CO_2 emissions grew rapidly, driven by a large increase in energy use. This was partly offset by reductions in fossil CO_2 intensity due to a switch from coal to oil and gas following market forces (e.g., economically exploitable natural gas resources) and environmental regulations (e.g., air pollution controls). From the early 1980s to the early 2000s, CO_2 emissions grew more slowly. The effect of continuing increases in energy use was partly offset by reductions in the fossil share of energy due to the expansion of nuclear power with a smaller contribution from changes in fossil CO_2 intensity in the 1990s. Changes in CO_2 emissions in the decade 2005-2015 are a break from historical trends in that they are supported by the largest decreases in the fossil fuel share observed since 1960, and by the only decrease in energy use sustained over a decade.

We further examine the decrease in energy use during 2005-2015 by decomposing the drivers of energy use into the associated growth in GDP, and the energy intensity of that GDP which also captures structural change in the economy (see Methods). The decrease in energy use in the 2005-2015 period is associated with low growth in GDP of around 1% per year in the peak-and-decline group, and reductions in the energy intensity of GDP of around –1% to –2% per year (Fig. S3). These reductions in energy intensity of GDP in 2005-2015 do not stand out compared to similar reductions observed since the 1970s (Fig. S3), indicating that decreases in energy use in the peak-and-decline group could be explained at least in part by the lower growth in GDP.

To gain insights into the likely persistence of the 2005-2015 trends, we compare the drivers of decreasing CO_2 emissions in 2005-2015 in the peak-and-decline group to the drivers of decarbonization in six global Integrated Assessment Models (IAMs)[14] used to explore future energy transformation pathways consistent with limiting climate change to two degrees of warming (Fig. S4). The IAMs project emission decreases over the period 2010 to 2020 in the EU and USA driven primarily by decreases in the fossil share of energy and by changes in the fossil CO_2 intensity (including carbon capture and storage in some models), with a smaller contribution from improvements in fossil utilisation rate. Changes in energy use do not contribute systematically to emissions reductions in these near-term IAM projections (Fig. S4; Table S6). However, the IAMs also assume annual GDP growth of 2.4% which is over double that observed in the past decade in the peak-and-decline group. For a fixed GDP growth[15], one widely-used IAM sees reductions in energy use make a growing contribution to emission decreases as climate targets become more stringent (Fig. S4). Although the IAM simulations are not designed for short-term analysis[16], this comparison suggests that if GDP returns to strong growth in the peak-and-decline group, reductions in energy use may weaken or be reversed unless strong climate and energy policies are implemented.

Finally, we examine the role of climate and energy policies as drivers of emissions reductions during 2005-2015. We separate policies broadly into three types according to whether they promote (1) renewable energy, (2) energy efficiency, or (3) climate change mitigation and adaptation (referred to below as 'climate policy frameworks'; see Methods). We use the numbers of policies adopted in law per country between 2005 and 2015, as a general indicator of the political commitment of a government to promote or restrict activities affecting carbon emissions[17]. Although a simple measure, numbers of policies are a useful first-order proxy of policy influence with precedent in the literature[18], as supported by a detailed study of the US states[19] and a comparative study among industrial countries[20].

In the peak-and-decline group, there were 35 [27-51] and 23 [15-35] policies per country in place by 2015 that promoted energy efficiency and renewable energy respectively (Table 2). This is substantially more than in either of the control groups (Table 2). Numbers of climate-change mitigation policies were also higher but more similar amongst the groups, with 10 [8-12] framework policies per country in the peak-and-decline group, compared to 7 [5-8] and 8 [5-10] respectively in control groups A and B.

In the peak-and-decline group, correlations between the drivers of emission decreases and the numbers of relevant policies were all of the expected sign. Decreases in energy use were correlated with the number of energy-efficiency policies ($r=-0.54$). Decreases in the fossil share of energy were correlated with policies on renewable energy ($r=-0.75$). Decreases in total emissions were correlated with the number of climate policy frameworks ($r=-0.54$; Table 2). Negative correlations indicate that larger reductions in emissions take place when more policies are in place. Decreases in energy intensity of GDP (see Methods) were also correlated with policies on energy efficiency ($r=-0.42$) but with significance only at the 90% level (Table 2).

In both control groups, the numbers of policies on energy efficiency were not significantly correlated with trends in energy use. However they were significantly correlated with trends in energy intensity of GDP. This suggests that policies have an effect on energy efficiency, but that effect is hidden by the effect of GDP growth on energy demand. For control group B (high GDP), trends in the fossil share of energy correlated positively with the number of policies on renewable energy ($r=0.51$). Renewables growth in these rapidly-expanding economies is adding additional capacity rather than displacing fossil fuels. Finally, in both control groups, there was a positive correlation between the trends in emissions and the number of climate-policy frameworks, which could reflect actions on climate change adaptation rather than mitigation. The number of climate policy frameworks was too small to test the effects of adaptation and mitigation policies separately.

These correlations provide indirect evidence that policies on energy efficiency may be playing an important role in driving emission reductions across countries, and that policies on renewable energy act to displace fossil fuel energy in the peak-and-decline group, but not elsewhere. Climate policy frameworks also appear to support emissions reductions but only in the peak-and-decline group, perhaps due to the larger number of policy frameworks in place. Although it is possible that the correlations could be due to other factors, the more mature implementation of a larger number of policies in the peak-and-decline group compared to the two control groups have a clear interpretation that energy and climate policies support emissions reductions.

Looking forward, the persistence of the decreases in emissions over the coming decades will depend primarily on structural decreases in energy use and in the share of fossils in the energy mix. To maintain and enhance decreases in energy use in the peak-and-decline group, policy support needs to be enhanced, particularly if GDP growth increases. Further support for reductions in energy use could tackle consumption[21,22] or the efficiency of energy-service provision as well as energy-conversion efficiencies in end-use technologies[23] (Table 2). More detailed representation of the policy and non-policy drivers of energy use in models should also help further explore the solution-space for deep mitigation[24]. The large-scale deployment of renewable energy is not sufficient by and of itself to lead to durable emissions decreases; it needs to be delivered within a framework of strong and supportive climate policies.

Finally, as significant as they have been, the emissions reductions observed and analysed in the 18 countries of the peak-and-decline group fall a long way short of the deep and rapid global decarbonisation of the energy system implied by the Paris Agreement temperature goals[3], especially given the increases in global CO_2 emissions in 2017 and 2018, and the slowdown of decarbonisation in Europe since 2014[25]. To limit climate change well below two degrees Celsius, global emissions in 2030 need to be about 25% below 2018 levels[26]. Recent acceleration in the deployment of renewable energy worldwide will only translate in to emissions reductions if accompanied by extensive measures to phase out the use of fossil fuels[27].

Table 1. Description of the drivers of emissions changes as represented in Equation (2). The examples describe factors that could lead to decreases in emissions.

Description	Short name	Examples of factors contributing to *declining* emissions
FE: Final energy, representing energy at the point of use	Energy use	• lower quantities of energy services consumed (e.g., less heating or mobility) • improved efficiency of energy services (e.g., insulated homes or higher occupancy vehicles) • improved energy-conversion efficiency of end-use technologies (e.g., more efficient boilers or cars) • electrification of heat engines (e.g., replacing internal combustion engines or gas- or diesel-powered mechanical equipment by electric motors)
C_f: Fossil final energy/Final energy, representing the share of fossil fuels in final energy	Fossil share	• decrease in direct use of fossil energy (e.g., gas for heating or coal for industrial processes) • increase in share of non-fossil low-carbon energy for electricity/heat generation or final use, including nuclear and renewables (e.g., wind, solar, hydro, biomass)
C_r: Fossil primary energy/Fossil final energy, representing aggregated energy use and losses from extracting fossil energy and converting it to fuels, electricity or heat for final consumption	Fossil utilisation rate	• improved thermal conversion efficiency (e.g., fossil power generation or refining) • lower transmission & distribution losses • lower fossil industry own use, including in extraction such as mining and in energy used by power plants and refineries (other than energy losses in conversion or refining processes themselves) • less use of refined/transformed fossil products (e.g., switch from electric to gas heating if the electricity is fossil-generated)

C_i: CO_2/Fossil primary energy, representing the carbon content of the fossil fuel mix	Fossil CO_2 intensity	• fuel switching towards lower-carbon fossil resources (e.g., gas) and away from higher-carbon fossil resources (e.g., coal) • reduction in the carbon content of coal and other fuels • more use of carbon capture and storage

Table 2. Correlations between numbers of policies and national trends in related CO_2 emission drivers during 2005-2015. Policies on energy efficiency are correlated with changes in energy use (adjusted for GDP growth in parenthesis, see Methods). Policies on renewable energy are correlated with changes in non-fossil energy. Climate framework policies are correlated with total changes in CO_2. Bold numbers are statistically significant at the 95% level.

	Energy efficiency	Renewable energy	Climate
Peak-and-decline group			
Number of countries with available data	18	18	18
Median [25-75 percentile] number of policies	35 [27-51]	23 [15-35]	10 [8-12]
Correlation with related CO_2 trend	**–0.54** (–0.42[a])	**–0.75**	**–0.54**
Control group A			
Number of countries with available data	24	30	30
Median [25-75 percentile] number of policies	10 [3-28]	11 [7-19]	7 [5-8]
Correlation with related CO_2 trend	–0.14 (**–0.61**)	–0.07	**0.56**
Control group B			
Number of countries with available data	13	31	31
Median [25-75 percentile] number of policies	2 [1-15]	6 [5-12]	8 [5-10]
Correlation with related CO_2 trend	0.55[a] (**–0.66**)	**0.51**	0.30

[a] Statistically significant at the 90% level

Data and Methods:

CO_2 emissions and energy data: CO_2 emissions are from fossil fuels only and are from the IEA Reference approach[28], which estimate CO_2 emissions using supply-side data of energy production. The final and primary energy data used in the decomposition come from IEA's World Energy Balances database [accessed July 2018][29]. Total primary and final energy are reported directly in the database, and we define the fossil share of final energy as direct final consumption of fossil fuels plus final consumption of heat and electricity derived from fossil sources. We also use four other sources of emissions to check the robustness of our analysis (see Supplementary Information): the Sector approach of the IEA; the national reports submitted to the United Nations Framework Convention on Climate Change (UNFCCC); BP; as well as emissions based on consumption accounting[7,30].

The 'peak-and-decline' group is selected based on those countries where emissions decreased significantly over the period 2005-2015 in at least three of the four databases, and where emissions also decreased significantly when accounted for on a consumption basis (Table S2; see also Supplementary information). It excludes Greece whose economy contracted severely during this period, and Jamaica because of suspected issues with the data. The two control groups include countries where emissions do not significantly decrease, with group A and B separated by their GDP growth rate below (group A) or above (group B) 3.5% per year.

GDP data are from the International Energy Agency, national currencies.

Policy data: We synthesized data on the cumulative number of policies promoting: (1) the use of renewable energy and (2) energy efficiency; and the cumulative number of (3) climate framework policies. Energy policy data is from the IEA/IRENA (International Renewable Energy Agency) Joint Policies and Measures database [accessed May 2018]. A climate framework policy is a legal act that seeks to provide a unifying basis for climate change mitigation and/or adaptation policy. We identified climate policies as frameworks if they were indicated accordingly by the Global Climate Legislation database, which is also the source for this data[10]. Given their broad scope, climate framework policies include a substantial share of measures targeting energy issues. However, the key difference between a climate framework policy and policies promoting the use of renewable energy and energy efficiency is that the latter were adopted as stand-alone pieces of legislation and exclusively target these two issues. In this analysis, policies such as the fraction of renewable energy target would be considered an energy policy under (1), even if the incentive for the policy is from addressing climate change. Many policies that encourage the deployment of renewable energy also encourage energy efficiency, so that (1) and (2) are themselves correlated. These variables include the total number of legal acts adopted nationally by 2015. Data were available for at least two of three policy drivers for countries in groups A and B.

Correlation analysis: All correlations presented use the Spearman ranked correlation so that each country has the same weight. Significance is assessed with a two-tailed t-test. We present the median and 25-75 percentile as a measure of the general trends found in most countries. Note that the sum of the medians of the energy decomposition does not necessarily add up to 100%.

Emission drivers: We separate different contributions to territorial CO_2 emissions (C) between final energy (FE); the fraction (C_f) of that final energy from fossil fuels (FE_{ff}/FE); the ratio (C_r) of fossil fuel primary energy over fossil fuel final energy (PE_{ff}/FE_{ff}); and the carbon intensity (C_i) of that fossil fuel primary energy (C/PE_{ff}), as follows:

$$C = FE \times \frac{FE_{ff}}{FE} \times \frac{PE_{ff}}{FE_{ff}} \times \frac{C}{PE_{ff}} = FE \times C_f \times C_r \times C_i \quad (1)$$

Examples of what these terms represent are provided in Table 2. The change in ΔC between two given years *t2* and *t1* is decomposed exactly using the Logarithmic Mean Divisia Index (LMDI) approach[31] as follows:

$$\Delta C = \Delta C_{FE} + \Delta C_{Cf} + \Delta C_{Cr} + \Delta C_{Ci} \quad (2)$$

where

$$\Delta C_X = \frac{C^{t2} - C^{t1}}{\ln C^{t2} - \ln C^{t1}} \ln\left(\frac{C_X^{t2}}{C_X^{t1}}\right) \quad (3)$$

We also further decompose *FE* of Eq. (1) into a contribution from *GDP*, and the energy intensity of *GDP* (E_i) to better understand the drivers of changes in energy demand:

$$FE = GDP \times \frac{FE}{GDP} = GDP \times E_i \quad (4)$$

Which extends Eq. (2) into:

$$\Delta C = \Delta C_{GDP} + \Delta C_{Ei} + \Delta C_{Cf} + \Delta C_{Cr} + \Delta C_{Ci} \quad (5)$$

The energy intensity of GDP includes all reductions in energy use per unit of GDP produced, and therefore includes energy intensity as well as structural changes in the economy (e.g. structural change from the production of goods to the production of services). See Supplementary Information for detailed results.

Acknowledgements

C.L.Q., C.W., G.P.G and D.v.V. received funding from the UK Department of Business, Energy and Industrial Strategy, as part of the "Implications of global warming of 1.5°C and 2°C project". A.J. and J.T. were supported by the European Commission COST Action IS1309 (INOGOV). C.W. also received funding from ERC Starting Grant #678799 for the SILCI project. We thank L. Leopold for assistance with the policy data.

Figures:

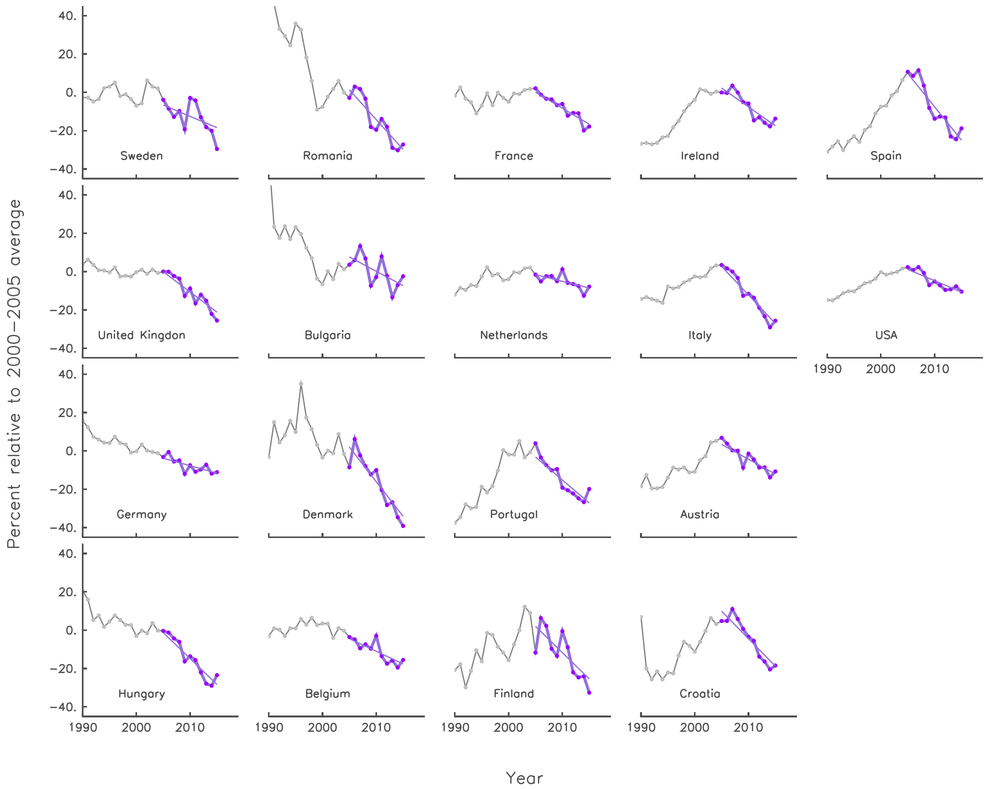

Figure 1. Change in CO_2 emissions from fossil fuel combustion for the 18 countries in the 'peak-and-decline' group (in percent). The 2005-2015 time period analysed here is emphasized in purple, with the linear trend shown for each country. Emissions are from the IEA reference approach[29]. The countries are generally presented in order of their approximate peak date, with some permutations for clarity. Change is relative to the 2000-2005 average.

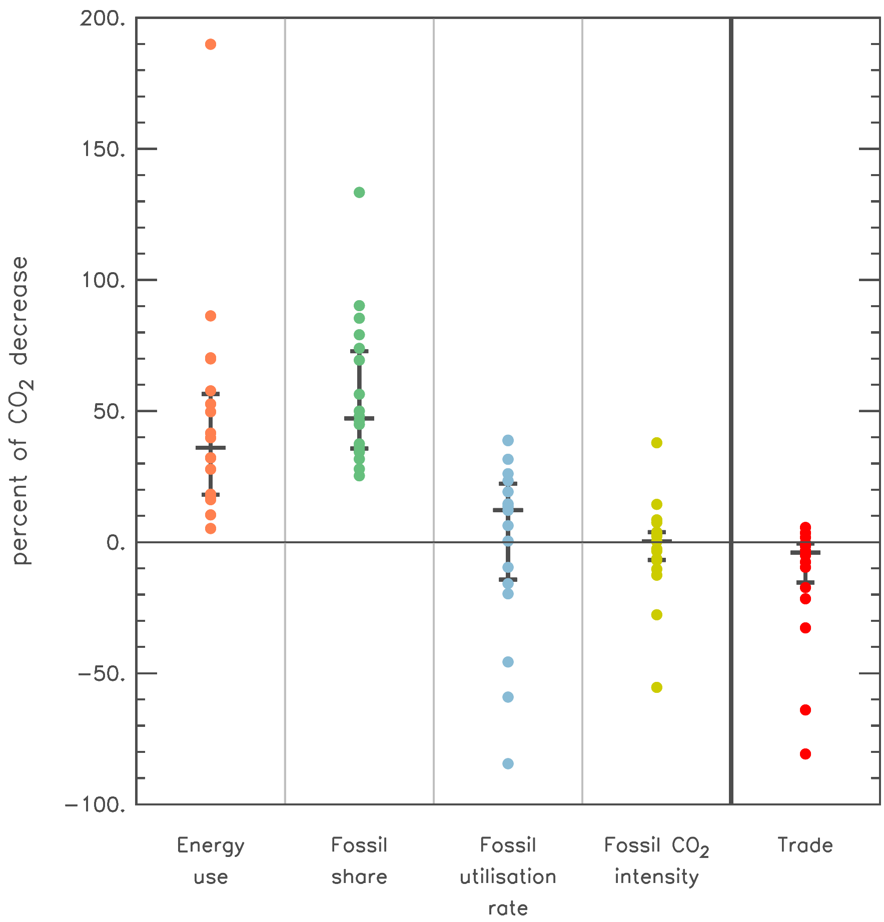

Figure 2. Contributions to the decrease in national CO_2 emissions from four physical drivers of change in energy production and use, as well as international trade, during 2005-2015. Each dot shows data for one country. Contributions are from changes in energy use (orange), fossil share of energy (green), fossil utilisation rate (blue), and fossil CO_2 intensity (yellow; the four right-hand terms of Eq. 2; Table 2). The transfer of emissions due to outsourcing consumption through trade is also shown (red). Energy data are from the IEA Reference approach[29]. Data are for the 18 countries in the peak-and-decline country group, with the median and 25-75 percentile (bars). See Supplementary Table S3.

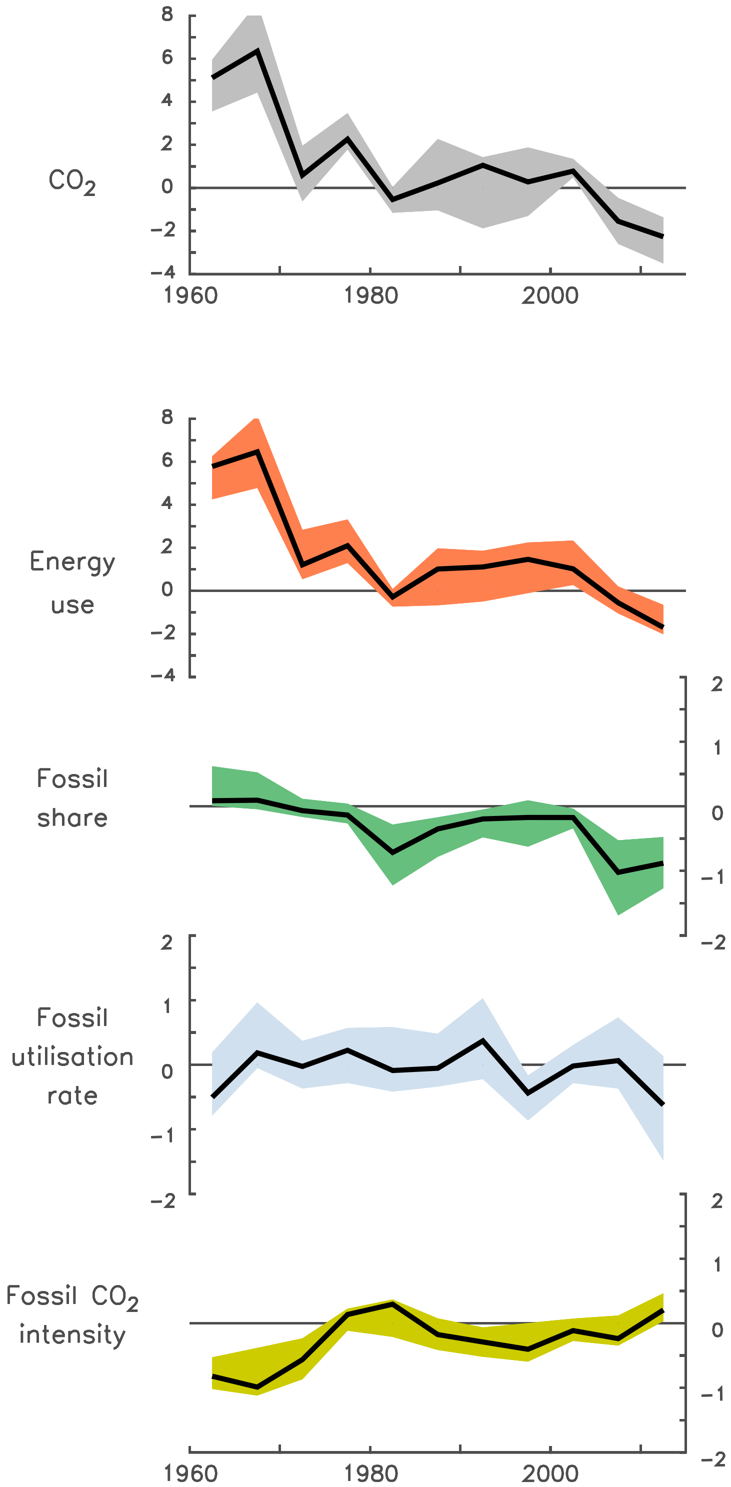

Figure 3. Time-series of changes in CO_2 emissions (top) and the contributions from changes in energy systems (percent per year). Contributions are from changes in energy use, the fossil share of energy, the fossil utilisation rate, and the fossil CO_2 intensity (Table 1). Data are for the peak-and-decline group as in Fig. 2, analysed in increments of 5 years from 1960 to 2015, showing the median and 25-75 percentile range.

References

1 Le Quéré, C. *et al.* Global Carbon Budget 2017. *Earth Syst. Sci. Data* **10**, 405-448, doi:10.5194/essd-10-405-2018 (2018).

2 Stocker, T., Qin, D. & Platner, G.-K. *Climate Change 2013 The Physical Science Basis*. (Cambridge University Press, 2013).

3 van Vuuren, D. P. *et al.* Carbon budgets and energy transition pathways. *Environmental Research Letters* **11**, doi:10.1088/1748-9326/11/7/075002 (2016).

4 Jordan, A. *et al.* Going beyond two degrees? The risks and opportunities of alternative options. *Climate Policy* **13**, 751-769, doi:10.1080/14693062.2013.835705 (2013).

5 IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 151 pages (2014).

6 Boden, T. A., Marland, G. & Andres, R. J. Global, Regional, and National Fossil-Fuel CO_2 Emissions, available at: http://cdiac.ornl.gov/trends/emis/overview_2014.html, last access: July 2017. (Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. , 2017).

7 Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 8903-8908, doi:10.1073/pnas.1006388108 (2011).

8 Davis, S. J. & Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences* **107**, 5687-5692, doi:10.1073/pnas.0906974107 (2010).

9 Peters, G. P. *et al.* Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Clim. Change* **7**, 118-123, doi:10.1038/nclimate3202 (2017).

10 Fankhauser, S., Gennaioli, C. & Collins, M. Do international factors influence the passage of climate change legislation? *Climate Policy* **16**, 318-331, doi:10.1080/14693062.2014.1000814 (2015).

11 Bernauer, T. & Böhmelt, T. National climate policies in international comparison: The Climate Change Cooperation Index. *Environmental Science & Policy* **25**, 196-206, doi:10.1016/j.envsci.2012.09.007 (2013).

12 Dubash, N. K., Hagemann, M., Höhne, N. & Upadhyaya, P. Developments in national climate change mitigation legislation and strategy. *Climate Policy* **13**, 649-664, doi:10.1080/14693062.2013.845409 (2013).

13 Lachapelle, E. & Paterson, M. Drivers of national climate policy. *Climate Policy* **13**, 547-571, doi:10.1080/14693062.2013.811333 (2013).

14 Riahi, K. *et al.* Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change* **90**, 8-23, doi:https://doi.org/10.1016/j.techfore.2013.09.016 (2015).

15 van Vuuren, D. P. *et al.* Alternative pathways to the 1.5 degrees C target reduce the need for negative emission technologies. *Nature Climate Change* **8**, 391-+, doi:10.1038/s41558-018-0119-8 (2018).

16 van Vuuren, D. P. *et al.* What do near-term observations tell us about long-term developments in greenhouse gas emissions? A letter. *Climatic Change* **103**, 635-642, doi:10.1007/s10584.010.9940.4 (2010).

17 Marcinkiewicz, K. & Tosun, J. Contesting climate change: mapping the political debate in Poland. *East European Politics* **31**, 187-207, doi:10.1080/21599165.2015.1022648 (2015).

18 Tosun, J. Environmental monitoring and enforcement in Europe: a review of empirical research. *Environmental Policy and Governance* **22**, 437-448 (2012).
19 Dietz, T., Frank, K. A., Whitley, C. T., Kelly, J. & Kelly, R. Political influences on greenhouse gas emissions from US states. *Proceedings of the National Academy of Sciences* **112**, 8254-8259, doi:10.1073/pnas.1417806112 (2015).
20 Knill, C., Schulze, K. & Tosun, J. Regulatory policy outputs and impacts: Exploring a complex relationship. *Regulation & Governance* **6**, 427-444, doi:10.1111/j.1748-5991.2012.01150.x (2012).
21 Girod, B., van Vuuren, D. P. & Hertwich, E. G. Climate policy through changing consumption choices: Options and obstacles for reducing greenhouse gas emissions. *Global Environmental Change-Human and Policy Dimensions* **25**, 5-15, doi:10.1016/j.gloenvcha.2014.01.004 (2014).
22 Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 degrees C target and sustainable development goals without negative emission technologies. *Nature Energy* **3**, 515-527, doi:10.1038/s41560-018-0172-6 (2018).
23 Wilson, C., Grubler, A., Gallagher, K. S. & Nemet, G. F. Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change* **2**, 780-788, doi:10.1038/NCLIMATE1576 (2012).
24 Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* **3**, 515-527, doi:10.1038/s41560-018-0172-6 (2018).
25 Le Quéré, C. *et al.* Global Carbon Budget 2018. *Earth Syst. Sci. Data* **10**, 2141-2194, doi:10.5194/essd-10-2141-2018 (2018).
26 Masson-Delmotte, V. *et al.* in *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* 32 (World Meteorological Organization, Geneva, Switzerland).
27 Figueres, C., Whiteman, G., Le Quéré, C. & Peters, G. P. Carbon emissions rise again. *Nature* (2018).
28 OECD/IEA. CO2 emissions from fuel combustion © OECD/IEA, www.iea.org/statistics, Licence: www.iea.org/t&c, accessed July 2017., (International Energy Agency/Organisation for Economic Cooperation and Development, Paris, 2017).
29 OECD/IEA. Based on IEA World Energy Balances database © OECD/IEA, www.iea.org/statistics, Licence: www.iea.org/t&c, accessed July 2018 (2018).
30 Le Quéré, C. *et al.* Global Carbon Budget 2016. *Earth Syst. Sci. Data* **8**, 605-649, doi:10.5194/essd-8-605-2016 (2016).
31 Ang, B. W. The LMDI approach to decomposition analysis: a practical guide. *Energy Policy* **33**, 867-871, doi:10.1016/j.enpol.2003.10.010 (2005).